Laser Damage Threshold Study

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a better resolution than 1 in 10. In addition, the better resolution occurs near the region of greatest interest, the damage threshold. A drawback to this measurement method is the large number of sites that must be irradiated. Using this test on small samples remains difficult however, it may be useful on larger samples such as the 2-inch optics.

The third laser damage measurement was discussed by Bass [2] and may possibly be used to determine the probability of damage at levels below the measured damage threshold. This work is based on the premise that even below the "0"-probability of damage level a part will exhibit damage given enough shots. The basis for this assumption is that laser damage is a statistical process. At low fluences the probability of damage may be vanishingly small. However, if a system is expected to accrue many shots, damage may again become statistically important. In this measurement a part is irradiated with one shot in a chosen number of sites and the percentage of sites which fail is recorded. The percentage of sites which fail are plotted on a logarithmic scale and a curve fitted to the points.

In this report all 10 of the laser mirrors were tested using the *DFM* method. Because of the large aperture of the parts, 5 samples measured using the *DFM* method were also measured using the *MDFM* method. This allowed a direct comparison between the results for the given test procedures. As part of this study 4 samples were laser conditioned after the initial *DFM* method. The parts again underwent a *DFM* test to determine the effect of the conditioning. The final sample was measured using *DFM* with the remainder of the part irradiated according to the Bass [2] technique.

3. Test Specifications

3.1 Test Setup

The following section describes the test setup and laser parameters utilized throughout this series of laser damage tests.

The laser source was a Gaussian reflectivity Nd:YAG oscillator. This system provided a Gaussian beam with better than 85% fit to Gaussian in the near field and better than 90% fit to Gaussian in the far field. This laser provided an output of 450 mJ at 1064 nm in a linearly polarized beam. The laser was operated with a PRF of 10 Hz with a 4 ns pulsewidth at the FWHM. The laser was passed through a 1/2 waveplate-thin film polarizer combination to allow for energy adjustment without thermally effecting the laser source. The laser energy was measured using a Scientech astral volumetric absorbing calorimeter capable of measuring 10 Watts of average power. A schematic of the experiment is shown in Figure 1. The laser was focused to a spot diameter of 1.01 mm using a slightly defocused Galilean telescope. This focusing system provides a long Rayleigh range mitigating beam size changes due to the possibility of a slight positioning error of the sample. The spot size was measured with a Spiricon LBA -100A beam analyzer. The beam analyzer provided a Gaussian fit and calculated the $1/e^2$ beam radius.

EXPERIMENTAL LAYOUT

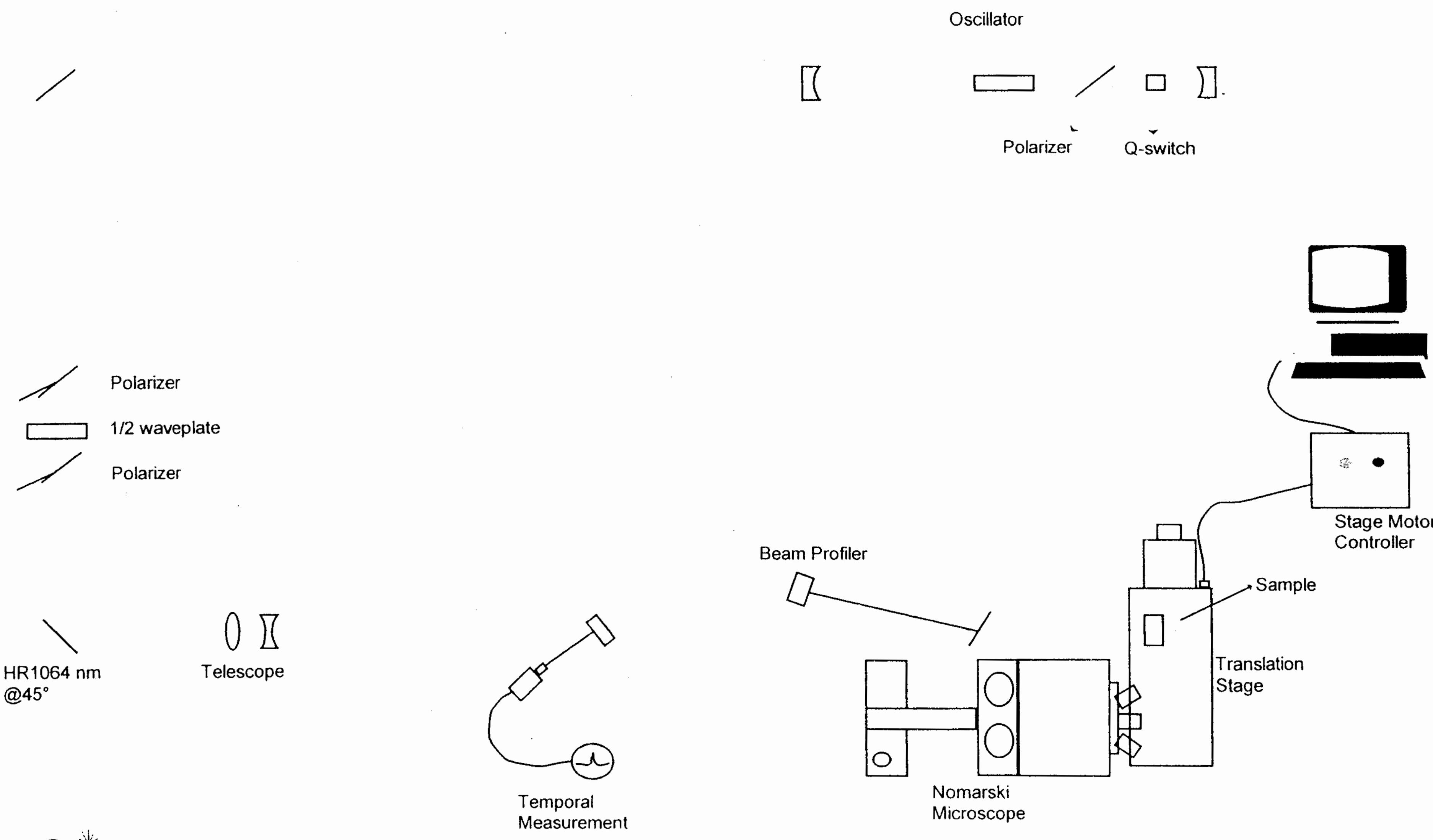

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Figure 1

The average of 30 frames was used to provide the $1/e^2$ beam diameter used in these experiments. Typical beam measurements and false color images of the beam intensity are shown in Appendix I. The beam diameter was rechecked whenever the laser was turned off and restarted. The samples were mounted in an aluminum holder such that the faces of the samples were at the same plane as the beam profiler CCD face. The samples were fixtured on motorized translation stages for both x and y (height) translation. An additional long throw translation stage was used to move the part from the beam path to a Nomarski microscope used for surface evaluation. This allowed the site to be observed, and if desired, photographed before and after irradiation.

3.2 Procedure

Parts were adjusted such that the Nomarski microscope observed the top center of the part. At this point the counters on the motorized stages were set to coordinate 0,0. The irradiation sites were indexed across the sample. When the edge of the optic was reached, it was translated up to test a new row. A standard irradiation pattern was utilized in these tests. This pattern avoids any overlapping of the various beams by using a center to center distance of 2 mm for the sites. As the samples were translated in the y direction the x direction was offset by 1 mm. This further reduced the likelihood of damage sites affecting their nearest neighbor. In most cases the damage occurred in small inclusion based sites, which did not propagate or extend beyond the 1 mm beam diameter. When catastrophic damage did occur, care was taken to avoid adjacent sites that may have had spatter or where coating matter was ejected. In all cases the mirror was irradiated for 200 shots barring the occurrence of damage.

3.3 Damage Tests

The laser damage frequency test was performed on all 10 of the optics provided. This test served as a baseline for the comparison of other tests. In addition, the testing of 10 samples provides some insight into the error of the laser damage measurement and the laser damage threshold spread from 10 samples all coated simultaneously.

The above mentioned procedure was used for all of these *DFM* tests. From this dead center, TDC, point the part was translated to the edge for the beginning of the test procedure. The laser was adjusted using the calorimeter for a nominal 40 J/cm^2 level and the required 10 sites were irradiated. This continued at different fluence levels until the addition of subsequent points did not change the calculated intercept by more than 10%. In all cases >7 sites were used in calculating the threshold. A level below the calculated threshold was then irradiated to assure the validity of the damage measurement.

The *MDFM* tests were similarly performed. However, instead of using 10 sites, the parts were irradiated until 5 sites exhibited damage. Upon the emergence of 5 damage sites the total number of irradiation sites was determined. The probability of damage was calculated by the division of 5 by the number of sites required to create the specified damage sites.

In the conditioning tests 10 sites at a time were irradiated. These sites were then re-irradiated in a *DFM* measurement. The comparison of the original *DFM* and the subsequent *DFM* measurement would reveal any conditioning effects.

The final part was irradiated using the Bass [2] technique. In this part the laser was set to fire only one pulse. The probability of damage was measured using 10 sites in the 10% - 100% range. Below 10% probability of damage the test was conducted in a similar manner to an Arenberg [1] test. Here the fluence was dropped significantly and the number of sites required to produce one damage event was measured.

4. Results

The data for each part is shown in Appendix II. Each entry includes the raw data, regression fit and calculated threshold. The calculated threshold for all of the parts and all of the tests is shown in Table 1. A *Laser Exposure Test Specification Sheet* is included as Figure 2 to help summarize the specifics of the test procedure.

Of the 10 mirrors that underwent initial DFM testing, all had exhibited damage thresholds in the 25 J/cm^2 range except for L-13. In all but one case the coatings were smooth and relatively free of inclusions and scatter. It is important to note that the damage observed on these mirrors can be divided into three categories. These included catastrophic damage, inclusion based damage which propagate through to the surface and inclusion-based damage which remain below the surface of the coating.

Catastrophic damage occurred at fluence levels in excess of 60 J/cm^2 and is marked by the complete destruction of the thin film. When this damage occurred, the bulk surface of the optic remained damage free with no pitting or cracking into the surface. Catastrophic damage was always centered on the laser irradiation area.

The second type of damage that was observed is best described as the formation of a small crater on the surface. In all cases the crater appears to extend down to the substrate surface and is accompanied by an outer raised ring. In some photographs the delamination of the coating at lower layers can be observed. These sites were typically 100 μm in diameter when irradiation was stopped after the first evidence of sparking. In many cases these craters were formed at sites which appeared as visible scatter sites in the coating prior to irradiation. It is also important to note that these damage sites did not appear at the center of irradiation. This indicates that the peak fluence in the central region of the beam was not required to produce these sites at certain fluence levels. This effect may explain the poor regression and scatter in some of the data. A visible spark that continued with subsequent laser pulses always accompanied the generation of these sites.

The third type of damage appeared as a raised or discolored area under the coated surface. Again, it appeared an inclusion had driven this damage. It is important to note however that no visible inclusion was seen prior to the onset of laser damage. It appears in the Nomarski micrographs that the coating is raised around the center of the inclusion with the center either depressed or raised. There also appears to be partial delamination of the coating around the damage site. These damage sites were particularly difficult to see with the microscope requiring great care in the adjustment of the polarizers to view these damage occupancies. A visible spark always accompanied this type of damage event however the spark only occurred on the first pulse of the laser. Subsequent pulses did not produce a visible spark.

Part Number	Damage Frequency Measurement (Plot a)	Modified Damage Frequenc Measurement (Plot b)	Conditioning Tests (Plot b)
L-9	18.32 ± 2.78 J/cm²	-	-
L-10	22.76 ± 1.58 J/cm²	24.19 ± 0.05 J/cm²	-
L-11	23.97 ± 2.00 J/cm²	23.99 ± 0.19 J/cm²	-
L-12	24.78 ± 0.92 J/cm²	24.59 ± 0.11 J/cm²	-
L-13	13.95 ± 1.63 J/cm²	13.80 ± 1.77 J/cm²	-
L-14	27.93 ± 1.66 J/cm²	31.54 ± 1.10 J/cm²	-
L-15	23.73 ± 2.03 J/cm²	-	26.01 ± 4.04 J/cm²
L-16	26.91 ± 3.17 J/cm²	-	26.59 ± 5.98 J/cm²
L-17	23.08 ± 3.52 J/cm²	-	24.69 ± 4.01 J/cm²
L-18	24.64 ± 10.47 J/cm²	-	26.17 ± 6.59 J/cm²
Mean	24.73 J/cm²		
SDOM	00.23 J/cm²		

Table 1: Damage Results Data

4.1 *MDFM* Measurements

As described above the *MDFM* method was used on 5 samples that had been previously irradiated using the *DFM* method. The data in Table 1 shows good agreement between the two methods. It should be added that the *MDFM* data shows excellent correlation of the probabilities of damage. As part of these tests, the parts were irradiated until 5 damage sites appeared. If additional area was available this number could be increased to further define the accuracy of the test.

After performing these *MDFM* tests we are quite impressed with the advantages this measurement provided. This method allows the measurement to be concentrated in the important region of the data near the absolute laser damage threshold. In addition, as one approaches the laser damage threshold the test provides better resolution than the 1 in 10 parts provided by the *DFM* method.

4.2 Conditioning Experiments

Parts L15-L18 underwent experiments to determine if laser conditioning could increase the laser damage threshold of the dielectric coating. In all cases, the sites were irradiated at a level below the damage threshold as measured during the *DFM.* On part L15 each site was conditioned for 100 shots at 20 J/cm^2 prior to the irradiation. Part L16 was conditioned for 1000 shots at the same fluence level prior to the subsequent irradiation Parts L17 and L18 were conditioned for 5000 shots at a similar fluence level at each site prior to irradiation. As shown in Table 1 the conditioning did not appear to have a significant, if any, effect on the laser damage threshold of the part.

4.3 Bass Tests

In addition to the *DFM* test part L-9 was used in an attempt to duplicate the work of Bass [(2)]. 7 sites were irradiated, 3 at or near the measured *DFM* threshold. It can be seen that laser damage occurred below what was defined as the laser damage threshold as the number of shots was increased. This data is included in Appendix II along with a logarithmic plot of the data. This plot shows the probability of damage becoming steep near the measured threshold. Fitting a curve to this line may provide some insight to the probability of damage at higher numbers of incident pulses.

4.4 Part L13 and L9

During the measurements part L-13 exhibited an extremely low laser damage threshold. Upon completion of this test numerous parameters of the irradiation laser and energy detection system were checked in an effort to expose an experimental error. None could be found in the setup and damage testing continued. Upon completion of part L-14, L-13 was slipped into the holder and irradiated for an additional 10 sites under which L-14 exhibited no damage. L-13 did exhibit damage on a number of sites leading us to believe the problem was with the part and not an experimental error. Subsequent examination of the coating surface revealed a very strange crystallization or possible stress induced deformation of the coating. This effect was visible over a large portion of the coating surface however did not occur in the region where the damage test was performed.

Part L-9 was the final part tested. This mirror also provided a slightly lower damage threshold that was seen in the other mirrors. Again the experimental setup was checked for any errors and none were found. The surface was carefully checked for deformation and again none was found. One explanation may be the fact that the part was previously tested using a smaller spot.

5.0 Conclusion

In this series of tests 10 laser mirrors were measured for laser damage threshold using the *DFM* method. Data derived from these tests indicated a damage threshold in the 25 J/cm^2 range. Visual inspection of the part, which did not fall in this range, indicated a surface defect that may have lowered the damage threshold. Laser induced damage was observed using a Nomarski DIC microscope and found to occur in three distinct modes

A *Modified Damage Threshold* test was performed on 5 mirrors and found to provide data in line with that from the *DFM* tests. In addition, it is felt the *MDFM* provided increased accuracy in the region near the laser damage threshold.

Conditioning experiments were attempted and results seem to indicate that laser conditioning did not effect the damage threshold of these samples.

Finally a Bass [2] type test was provided in order to provide insight into the possible lifetime issues associated with the mirror coatings.

6.0 References

1. Johnathan W. Arenberg, "Design of a Certification Test for Laser Damage Resistance," Laser Induced Damage In Optical Materials SPIE Vol. 2714 (1995) : 119

2. Michael Bass and Harrison H. Barrett, "The Probability and Dynamics of Damaging Optical Materials with Lasers," Raytheon Research Division.

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LASER EXPOSURE TEST SPECIFICATION SHEET CERTIFICATE OF COMPLIANCE

DATE: March 25, 1997

CUSTOMER: NASA Goddard Space Flight Center

ADDRESS: Greenbelt, MD 20771-0001

ATTN: Mr. Joe Dallas

P.O. NUMBER: S-59357-Z

SERIAL NUMBER: N/A

PART/RUN NUMBER: L-9 through L-18

TEST TYPE: Laser Damage Threshold

TEST LOG NUMBER: 7008-DT

SAMPLE SIZE: 2" Diam.

COATING TYPE: HR

TEST WAVELENGTH: 1064 nm

POLARIZATION: Linear

PULSEWIDTH (FWHM): 4 ns

SPOT DIAMETER ($1/e^2$): 1.010 mm

TEST METHOD: Various

QUANTITY: 10

SUBSTRATE MATERIAL: Fused Silica

TEST PREP: Acetone Drag, Methanol Drag

INCIDENCE ANGLE: 0°

PRF: 10 Hz

TEST BEAM PROFILE: TEM_{00}

AXIAL MODES: Multiple

NUMBER OF SITES: Variable

SHOTS/SITE: Variable

DAMAGE DEFINITION: Spark, increased He-Ne scatter. Visible damage as seen with 100x Nomarski microscope.

COMMENTS: Photomicrographs enclosed.

Spica Technologies certifies that this sample has been exposed to the conditions described above. All damage and calibration data are maintained on file. All instrumentation calibration is traceable to NIST.

Test conducted by ____________ MAR. 25, 1997
Date

Figure 2